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## Study of the Pressure Drop and Thermal Performance of An Air-Air Heat Exchanger for Aero-Engine Application

Lu Haiying<sup>a</sup>, Lv Duo<sup>a</sup>, Yu Xiao<sup>a,b,\*</sup>, Li Yi<sup>a</sup>, Shen Yi<sup>a</sup>, Dong Wei<sup>c</sup>

<sup>a</sup>Shenyang Aero-engine Research Institute, Aviation Industry Corporation of China, Shenyang, 110015, China

<sup>b</sup>National Key Laboratory on Aero-engines, School of Jet Propulsion, Beijing University of Aeronautics and Astronautics, Beijing, 100083, China

<sup>c</sup>Shanghai Jiao Tong University, Shanghai, 200240, China

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### Abstract

In this paper, a comparison of the pressure drop and thermal performance between an improved air-air heat exchanger and a former one designed for aero-engines applications is performed. In order to model the flow field through the heat exchanger, both computational fluid dynamics (CFD) and experiment method were used. For this purpose, a model of the heat exchanger has been constructed and mounted in the test section of a wind tunnel to investigate the pressure drop and heat transfer performance of different heat exchangers by changing the tube geometry. And the exact tube bundle arrangement of the heat exchanger was simulated in CFD. The results are compared with experimental data for the same inlet conditions and were found to be in agreement. The results showed that the pressure drop of the improved heat exchanger reduced by over 10% and heat transfer increased by almost 25%. Thus, both the CFD and the experiment method could be used for the detailed investigation of the flow field and heat transfer performance of the heat exchanger so that useful conclusions of heat exchangers designed for aero-engines could be derived.

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\* Corresponding author. Tel: 86-024-24286318, Fax: 86-24-24285673

E-mail address: [yuxiao606@163.com](mailto:yuxiao606@163.com)

## 1. Introduction

In modern aero-engines, heat exchangers are incorporated into gas turbines to get a better performance. Based on previous studies, heat exchanger designs for an aero engine are recuperators, intercoolers, and cooled cooling-air system (CCA). A typical CCA system was shown in Fig.1.

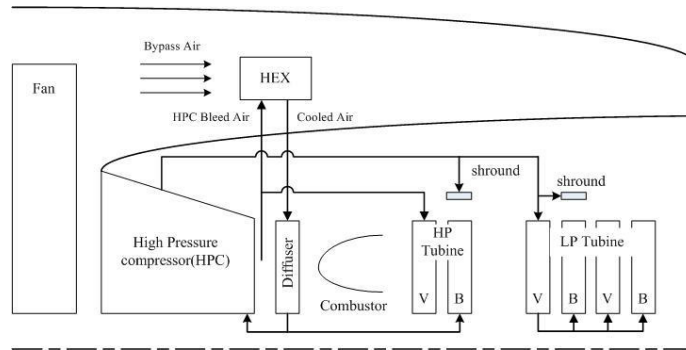


Fig.1.CCA system

The cooling air is provided by a high-pressure compressor air bleed and the heat is transferred by the heat exchanger of CCA system. This may allow a higher turbine entrance temperature and can reduce the compressed air bleed. Cooled cooling air can provide benefits that include an increase in turbine efficiency as well as the creation of additional air for combustion. The heat exchanger is the core technology so that the research of pressure drop and heat transfer performance of heat exchanger is of great significance for aero engine investigation.

## 2. Heat exchanger design

Investigation involving flow-over-tube bundle heat exchangers, consisting of either elliptical or circular tubes, have been the subject of numerous experimental and numerical works. The problem was taken as a 2D, steady flow and heat transfer problem. The solved equations are the continuity equation, Eq.(1), the momentum equations, Eq.(2) and Eq.(3), and the energy equation Eq.(4) and Eq.(5).

### 2.1. Continuity

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \quad (1)$$

### 2.2. Momentum

$$\frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left[ 2\mu \left( \frac{\partial u}{\partial x} - \frac{1}{3} \nabla \cdot \vec{V} \right) \right] + \frac{\partial}{\partial y} \left[ \mu \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right] \quad (2)$$

$$\frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho vv)}{\partial y} = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial y} \left[ 2\mu \left( \frac{\partial v}{\partial y} - \frac{1}{3} \nabla \cdot \vec{V} \right) \right] + \frac{\partial}{\partial x} \left[ \mu \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right] \quad (3)$$

### 2.3. Structure Energy

$$C_p \left( \frac{\partial(\rho u T)}{\partial x} + \frac{\partial(\rho v T)}{\partial y} \right) = \left[ \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) \right] - p \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) + \Phi \quad (4)$$

Where

$$\Phi = \mu \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right)^2 + 2\mu \left[ \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 \right] - \frac{2}{3} \mu \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)^2 \quad (5)$$

The characteristic Nusselt number for the heat exchanger tube array is defined in Eq.(6):

$$Nu = \frac{hd}{\lambda} \quad (6)$$

where  $h$  is the heat transfer coefficient,  $d$  is the equivalent diameter of the tube of the heat exchanger and  $\lambda$  is the thermal conductivity of air. In this paper we change the former circular tube of the air-air exchanger to an improved elliptical tube so as to the decrease of the equivalent diameter to achieve a higher heat transfer coefficient.

### 3. Experimental apparatus

The experiment was finished on the multifunctional heat exchanger facility in National Key Laboratory on Aero-engines of BUAA. The experiment system mainly includes a wind tunnel, pressure and temperature testing system as shown in Fig.2. A model of the heat exchanger has been constructed and mounted in the test section of a wind tunnel. The improved heat exchanger model is corresponding to the straight part of the heat exchanger core geometry and consists of 54 elliptical tubes, while the former one uses circular tubes instead. For the experimental measurements, the air inlet temperature was set at 273K to 293K and the vapor inside the tube was set at 373K. The air flow into the wind tunnel to simulate the cold source and the vapor flow into tube bundles treated as hot gas. The maximum Reynolds number of the inlet air was set to  $4 \times 10^4$ . Thus the pressure drop and heat transfer performance of the heat exchanger core could be researched.

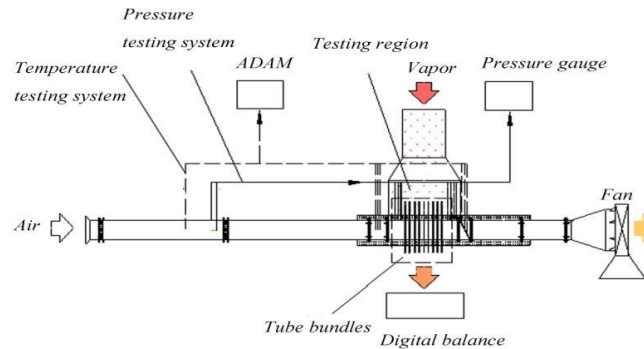


Fig.2.Experiment system

### 4. CFD method

The computational domain consists of one characteristic flow passage, presented in Fig.3. The flow field solution is performed under a 2D approach. Thus, a computational grid of 386,425 elements was created. During the grid

creation process, the computational field was divided into different parts and special care was given to the part where significant variations in the flow quantities were expected and the tube flow boundary layer, as presented in Fig.3

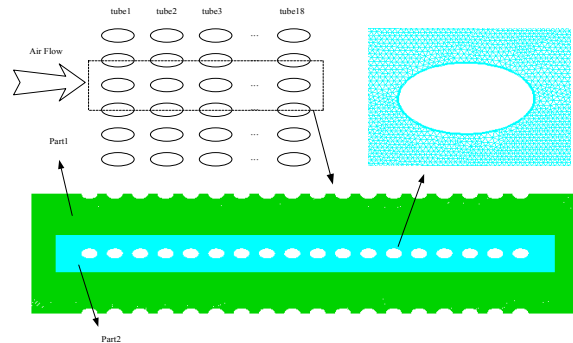
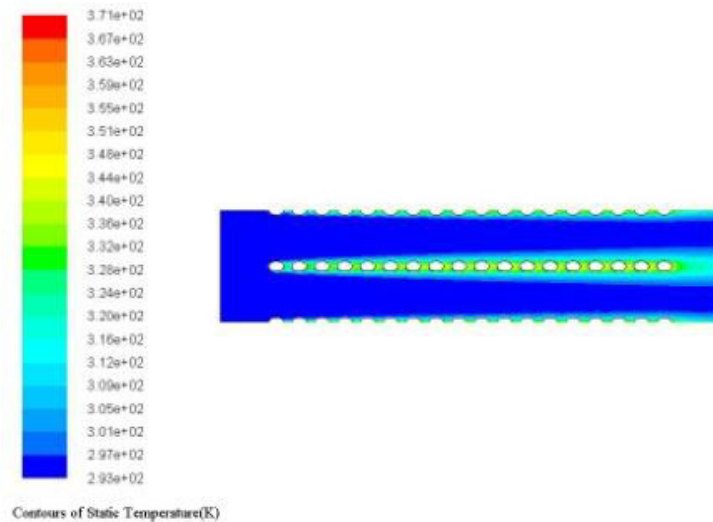


Fig.3.Heat exchanger computational region

## 5. Results

The temperature, pressure field and the streamline of the heat exchanger of CFD results were shown in Fig.4 and Fig.5 while inlet gas temperature is 293K and inlet gas velocity is 40m/s. As can be seen there are vortices between the tubes and this may influence the heat transfer performance. The investigation was performed under different gas inlet velocity in both numerical simulation and experimental measurements.



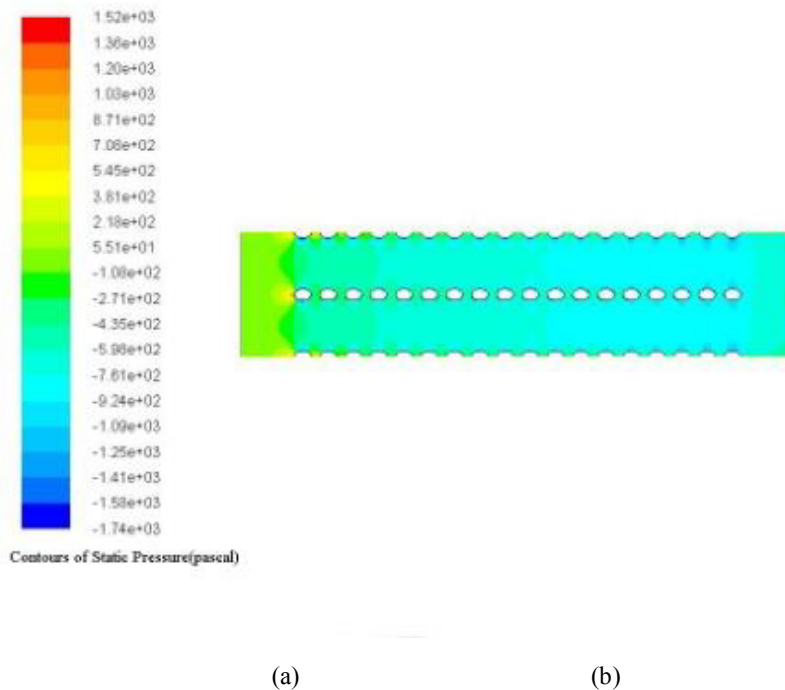


Fig.4. (a) Temperature and (b) pressure field

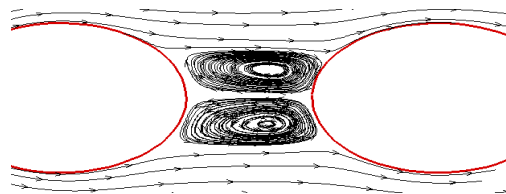


Fig.5. Streamline of velocity of heat exchanger core

For the investigation of the pressure drop and the thermal performance of the heat exchanger core, the Nusselt number of the experimental measurements is taken to be considered. The results showed that the pressure drop of the improved heat exchanger reduced by over 10% and heat transfer increased by almost 25%.

In Fig.6 a comparison of the measured and calculated heat transfer coefficient of the heat exchanger core is shown. The plot consists of the numerical and the experimental results of both circular and elliptical tubes. The heat transfer coefficient increases with the velocity of the inlet gas in both experimental measurements and numerical results. And it can be also founded that the numerical results fits well with the experimental measurements and the correctness of the numerical method is proved. For the comparison the numerical heat transfer coefficient was calculated by using the same definition as the experimental results. The heat transfer coefficient of elliptical tubes is larger than the circular tubes and this could cause an increase of the heat transfer performance of the heat exchanger core.

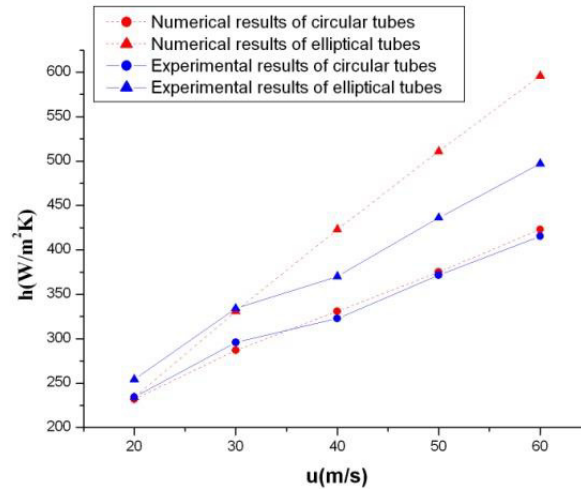


Fig.6. Heat transfer coefficient for different tube geometry

From both the experimental and the numerical results it can be founded that the heat transfer coefficient of elliptical tubes is larger than that of the circular tubes. So we can conclude that circular tube array could achieve a better heat transfer performance than circular tube array in the same fluid situation. The mainly reason for this character is that for the heat transfer inside the tube, the heat transfer could be considered by Eq.(7):

$$Nu = 0.27 Re^{0.63} Pr^{0.36} \quad (7)$$

And outside the tube we can use Eq.(8)

$$Nu = 0.236 Re^{0.62} Pr^{0.33} \quad (8)$$

Where Nu is the Nusselt number of the fluid, Re and Pr are the Reynolds number and Prandtl number. It is also known that the heat transfer coefficient is defined as Eq(9):

$$h = \frac{Nu \cdot \lambda}{d} \quad (9)$$

Where  $\lambda$  is thermal conductivity and d is the equivalent diameter of the tube. For elliptical tubes d is defined as Eq(10):

$$d = \frac{ab}{\sqrt{(a^2 + b^2)/2}} \quad (10)$$

a, b are the major and minor axis of the tube. The heat transfer coefficient decrease with the equivalent diameter of the tube and the equivalent diameter of circular tubes is proves bigger than that of elliptical tubes. From the equation above it is obviously that elliptical tubes could achieve a higher heat transfer coefficient. More specially for the heat transfer outside the tube, the vortices depart from the elliptical tube bundle later than in circular tubes so that the elliptical tube bundle could have a better heat transfer performance. For the both reason mentioned above, the elliptical tubes could achieve a better heat transfer performance.

Fig.7 display the pressure drop coefficient of the tube arrays on both the elliptical and circular tubes. In both the experimental measurements and the numerical simulation the pressure drop coefficient was defined as Eq.(11):

$$\xi = \frac{f}{\frac{1}{2} \rho u^2 A} = \frac{\Delta p}{\frac{1}{2} \rho u^2} \quad (11)$$

Where  $\Delta p$  is the pressure drop of the gas flow through the heat exchanger core and  $u$  is the velocity of the gas flow into the wind tunnel. And the distribution are presented in relation to a characteristic Reynolds number defined as Eq.(8):

$$Re = \frac{ud}{\nu} \quad (12)$$

As can be seen, for the numerical and experimental results the pressure drop coefficient of the elliptical tubes is smaller than that of the circular tubes and this is of great significance for the aero-engine heat exchanger design. We can achieve a better heat transfer performance with a lower pressure loss. Noticeably, in the both cases the experimental measurements distribution fits well with the numerical results. The pressure drop coefficient first increase then almost unchanged with the gas Reynolds the distribution is almost the same.

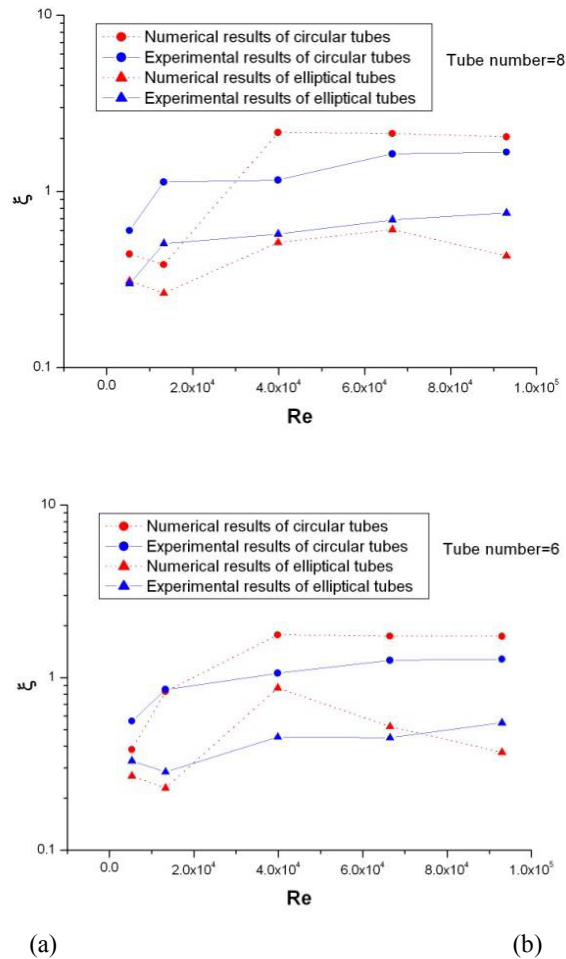


Fig.7. Pressure drop coefficient for different tube array: (a) tube number  $z=8$  (b) tube number  $z=6$

In order to investigate the pressure loss of different tube arrays, a pressure loss characteristic number  $C_z$  was defined as Eq.(13):

$$Cz = \frac{\xi_z}{\xi_{\max}} \quad (13)$$

Where  $\xi_z$  is the tube array pressure drop coefficient of tube number  $z$  and  $\xi_{\max}$  is the tube array pressure drop coefficient of the eighteenth tubes in this experiment. Fig.8 display the characteristic number  $Cz$  on various tube numbers of both experimental measurements and numerical results at the typical gas Reynolds number of 39866 and 66440. It can be founded that  $Cz$  increases with the number of the tube and at different gas Reynolds number the  $Cz$  distribution is almost equal. Obviously the experimental measurements and the numerical results are of great fitness. More specially, for different tube arrays according to the numerical approach the  $Cz$  can indicates the pressure drop of the total heat exchanger core conveniently.

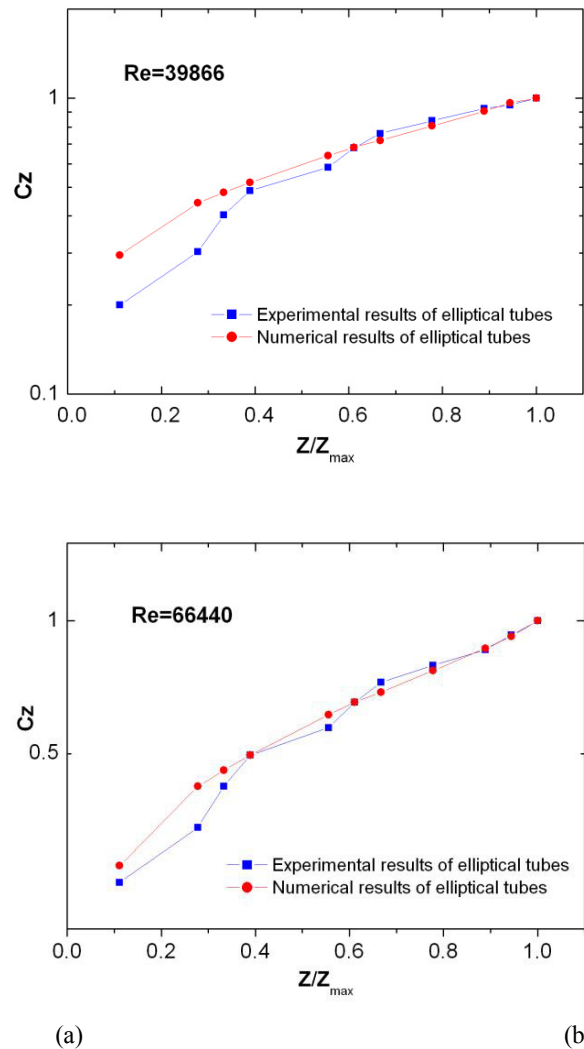
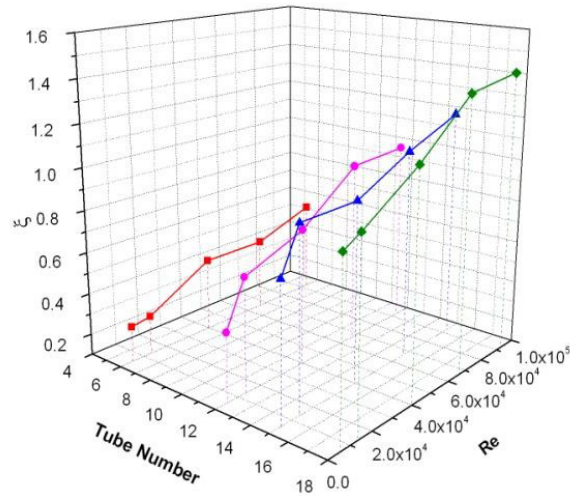


Fig 8.  $Cz$  for different tube numbers, (a)  $Re=39866$  (b)  $Re=66440$

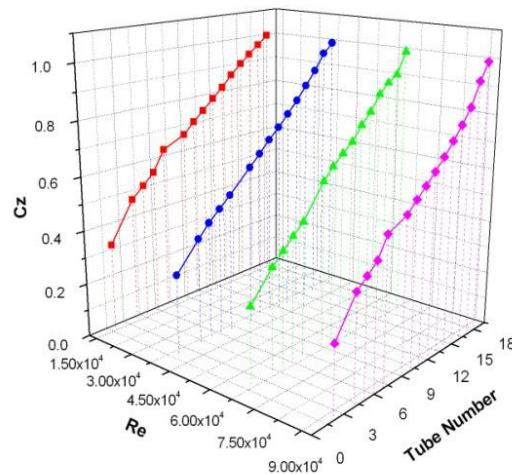
For the experimental measurements, the pressure drop coefficient of elliptical tubes under a series of Reynolds number from to is considered in Fig.9(a). As can be seen the pressure drop coefficient increases with the number



of the tubes and the gas Reynolds number and the influence of tube number is significant. Further more, based on the definition and using the characteristic number  $C_z$  to describe the pressure drop of different tube arrays on various gas Reynolds number. A comparison of  $C_z$  is show at Fig.9(b). The results of  $C_z$  distribution are presented mainly in relation to the tube number and the influence of gas Reynolds number is small.  $C_z$  for each gas Reynolds number differs according to the difference of tube number and for all at different Reynolds number the distribution of  $C_z$  is almost equal. This is of great significance for engineering application. In the heat exchanger design for aero-engine applications, the pressure loss is of great importance for the heat exchanger performance. In the design process, we can get the pressure drop coefficient by using the characteristic number  $C_z$  and the pressure drop coefficient for the maximum number of tube array. For the parameter that the experimental method cannot be reached, this numerical simulation could be used.



a pressure drop coefficient



b characteristic number  $C_z$

Fig.9.Cz for different tube numbers and Reynolds number

## 6. Conclusion

1) The pressure drop and the heat transfer are the main influencing factors on the performance of aero-engine heat exchangers. The use of the improved elliptical tubes can lead to less pressure loss and better thermal performance of heat exchanger and is of great significance for aero engine applications.

2) The experiment and CFD results showed that the pressure drop of the improved heat exchanger reduced by over 10% and heat transfer increased by almost 25%. The distribution of characteristic number Cz could be extended to current pressure loss estimate for different tube arrays.

3) By using the elliptical tubes, the heat exchanger could achieve a better heat transfer performance with less pressure drop. The mainly reason is that the elliptical tubes reduce the equivalent diameter and enhance the heat transfer.

4) Both the CFD and the experiment method could be used for the detailed investigation of the pressure drop and thermal performance of the heat exchanger so that useful conclusions of heat exchangers designed for aero-engines could be derived.

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